

1 Introduction, Turbomachinery, Applications, Types

Turbomachines are devices within which conversion of total energy of a working medium into mechanical energy and vice versa takes place. Turbomachines are generally divided into two main categories. The first category is used primarily to produce power. It includes, among others, steam turbines, gas turbines, and hydraulic turbines. The main function of the second category is to increase the total pressure of the working fluid by consuming power. It includes compressors, pumps, and fans.

1.1 Turbine

Turbines serve as power producing devices. Figure 1.1 exhibits a large steam turbine used for base load power generation. It consists of an integrated *high pressure* (HP), an *intermediate pressure* (IP), and two identical *low pressure* (LP) components.

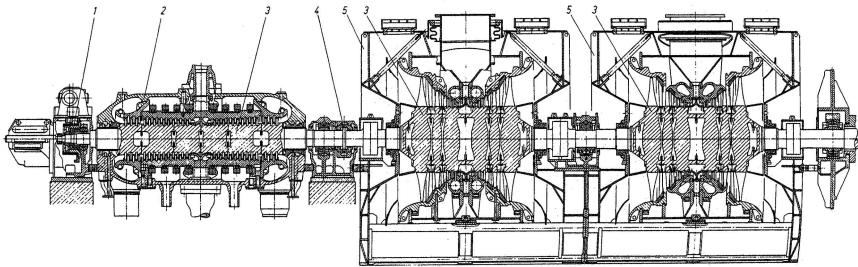


Fig 1.1: A large steam turbine for base load power generation with an integrated high pressure, an intermediate pressure part (left), and two identical double inflow low pressure turbine components (Brown Boveri & Cie design)

Each component incorporates a number of *stages* consisting of *stator-* and *rotor-blading*. Steam at a given level of total energy, enters the HP-turbine component shown in Fig. 1.2, passes through the first stator row, and undergoes a certain degree of deflection, which is necessary to provide appropriate inlet conditions for the rotor row that follows. The stator blades are attached to the inner casing, which is under higher pressure than the outer one, Fig. 1.2. During the course of deflection, the working fluid is accelerated. As a result, the potential energy of steam is partially converted into kinetic energy, which is used in the following rotor blading. Due to the rotational motion of the rotor, a part of the total energy is converted into mechanical energy, generating shaft power. This process is repeated in the following stages until the exit

conditions are reached. The HP-turbine component is characterized by a relatively small blade height compared to the LP-component. As seen in Figs. 1.1, the cross sections of the integrated HP- and IP-part, experience only a moderate change due to a moderate increase in specific volume. In contrast, the specific volume changes drastically within the LP-part, requiring an excessive opening of the cross section to accommodate large blade heights.

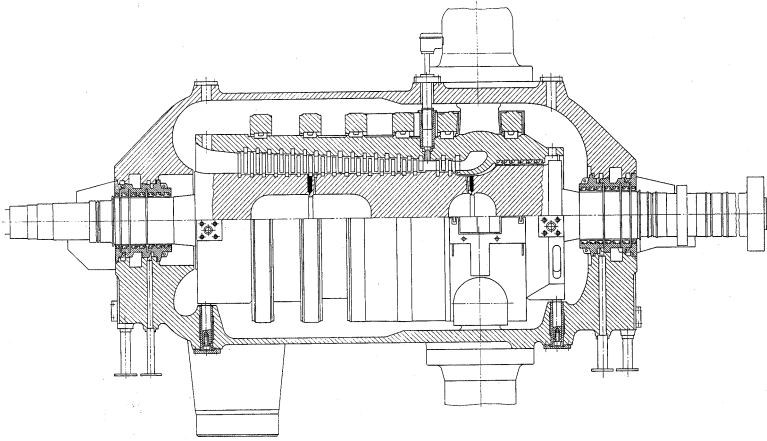


Fig. 1.2: A typical HP-steam turbine with the first control stage, inner and outer casings and labyrinth seal packets, (ABB Power Generation)

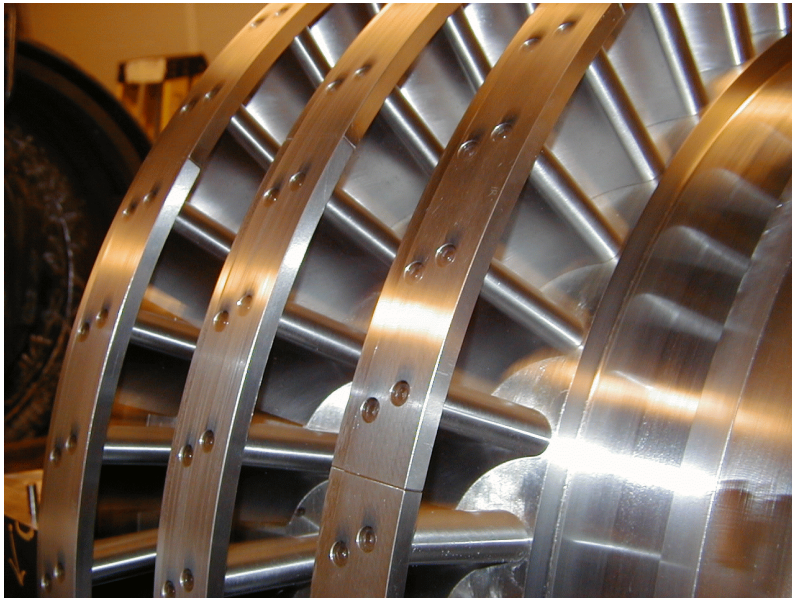


Fig. 1.3: A three stage high pressure research turbine at *TPFL*. The blades are cylindrical with tip shroud to reduce the tip leakage losses.

Figure 1.2 shows an HP-turbine with a control stage and a multi-stage arrangement attached to a shaft that consists of three welded discs. It also reveals the labyrinths installed on both shaft ends to seal the high pressure steam against the atmospheric pressure. HP-turbine blades may have cylindrical (2-D) or three-dimensionally (3-D) bowed blades. Figures 1.3 and 1.4 show two different rotors with the 2-D cylindrical and 3-D bowed blade. The cylindrical blades are more cost effective and easier to manufacture than the 3-D bowed blades, however, their efficiency is below the 3-D blade efficiency.



Fig. 1.4: A three-stage high pressure research turbine with bowed blades and tip shroud to reduce secondary flow and tip clearance losses, *TPFL*

Details of a typical LP-turbine component are shown in Fig. 1.5. Characteristic features of this component are the symmetric configuration of the shaft and the blading, as well as the steep increase in blade height. The symmetric configuration is used to cancel the axial thrust on the bearings. In contrast to the HP-components with a high back pressure, the back pressure of LP-component corresponds to the condenser pressure, which is a fraction of the environmental pressure and strongly depends on environmental temperature.

Figure 1.6 exhibits the details of a typical labyrinth seal. The kinetic energy of the jets through the labyrinth clearance is dissipated within the labyrinth chambers preventing the leakage mass flow to become excessive. While the HP-labyrinths reduce the steam leakage to the atmosphere, the LP-seals prevent the atmospheric air to penetrate into the LP-turbine, disrupting the condenser vacuum.

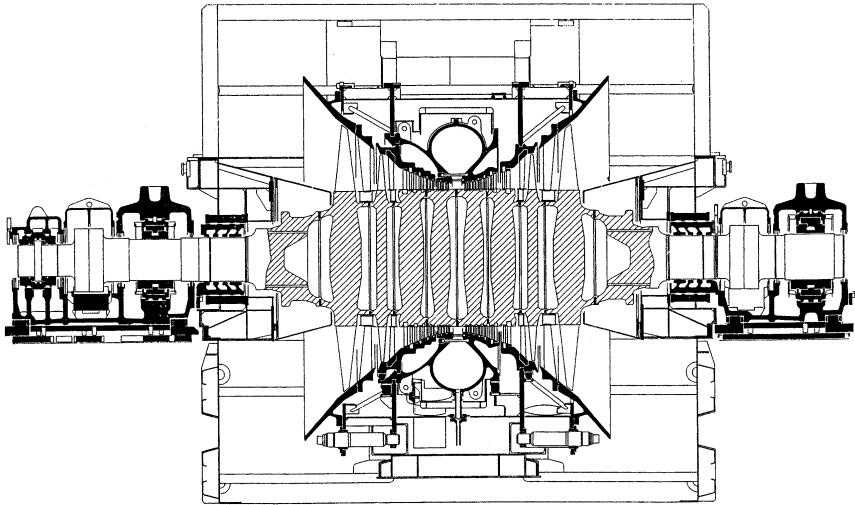


Fig. 1.5: A double inflow low pressure turbine component (ABB Power generation

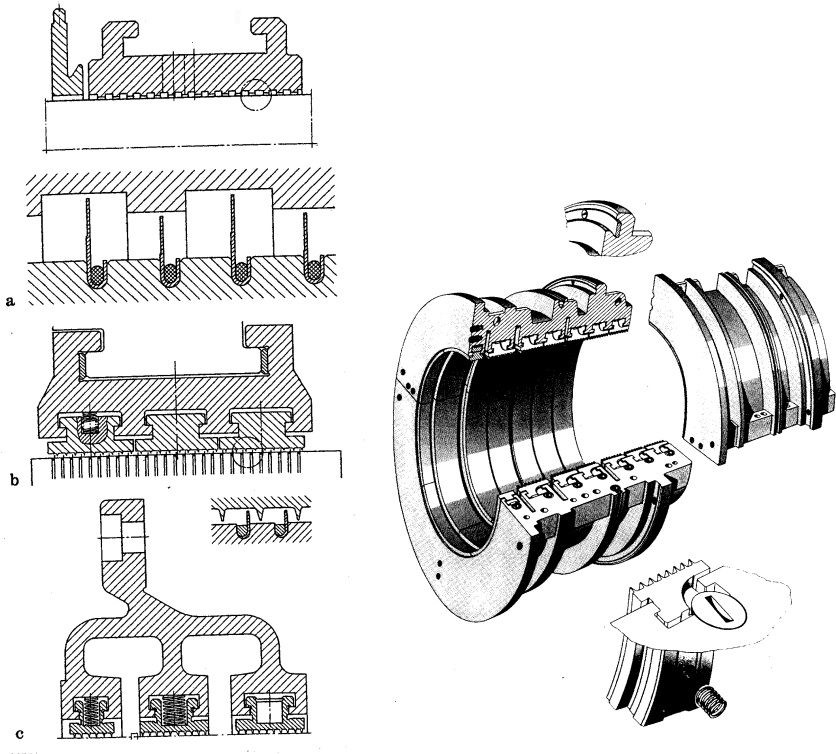


Fig. 1.6: HP-turbine labyrinth seals

1.2 Compressor

The function of a compressor is to elevate the total pressure of the working fluid. According to the conservation law of energy, this total pressure increase requires external energy input which must be added to the system in the form of mechanical energy.

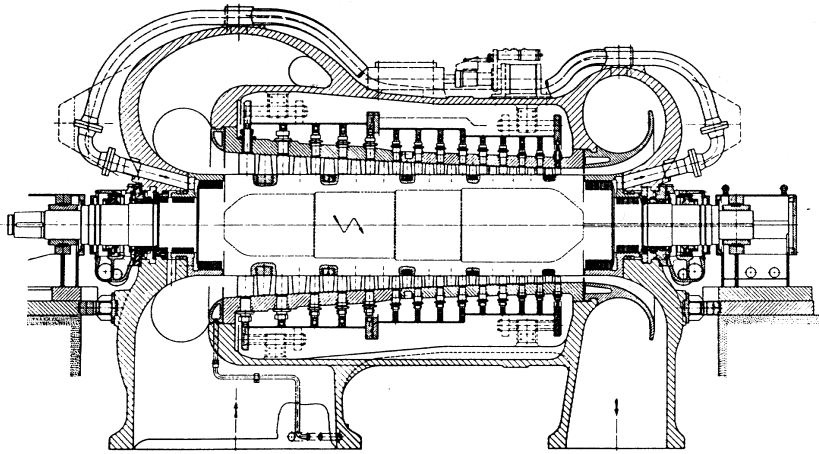


Fig. 1.7: A multi-stage high pressure compressor (Sulzer)

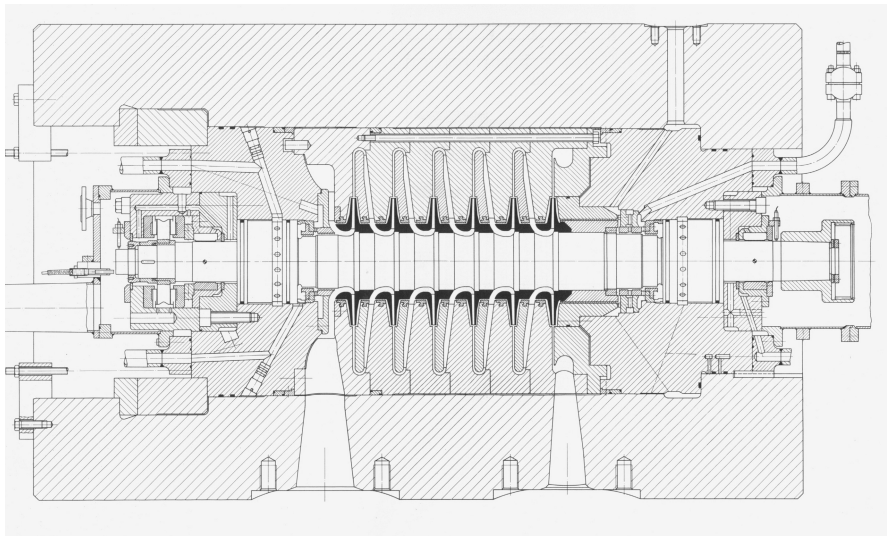


Fig. 1.8: A high pressure centrifugal compressor with an exit pressure of up to 900 bar and a volume flow rate of up to 300,000 m³/h (MANNESMANN-DEMAC)

The compressor rotor which is driven either by an electric motor or a turbine, exerts forces on the fluid medium and therefore increases its pressure. Compressors are utilized, among others, in pipeline systems, chemical industry, steel production for blowing oxygen and oxygen enrichment of blast furnace air, biological sewage treatments, and gas liquefaction. In power generation and aircraft gas turbines the compressor component provides the pressure ratio essential for maintaining the process of power or thrust generation. Pumps are a special type of turbo compressor with liquids as working fluids. Pumps have a wide application field. In base load power generation they serve as the feed water pumps and main condenser pumps to elevate the steam pressure from condenser pressure to boiler pressure. Pumps are also major components in rocket engines.

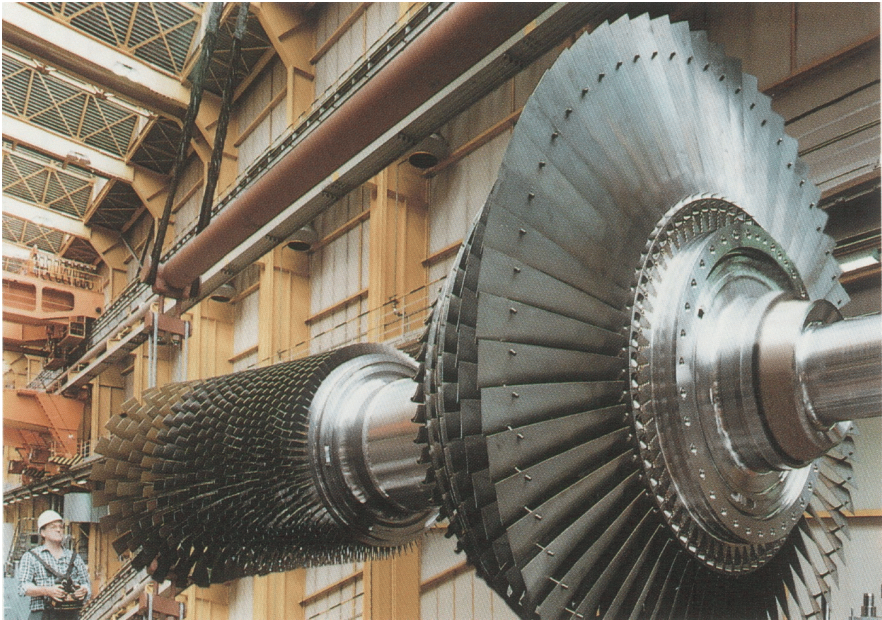


Fig. 1.9: Rotor unit of a heavy duty gas turbine with multi-stage compressor and turbine, compressor pressure ratio 15:1, (ABB-GT13E2)

Figure 1.7 shows a high pressure axial compressor with a carefully designed inlet nozzle and exit diffuser. To balance the axial thrust originating from the pressure difference, the pressures on both sides of the shaft are balanced through a connecting pressure equalizing pipe. Figure 1.8 shows major design features of a high-pressure compressor with a wide variety of applications. The area of application for these types of compressors include chemical and petrochemical industries, ammonia plants, urea and methanol synthetics, gas pipeline, and nuclear reactors. Figure 1.9 shows the integration of the compressor component onto the shaft of a heavy duty power

generation gas turbine. The compressor component provides the optimum process pressure ratio of 15:1 and a design flow of 525 kg/s that are essential for generating a power output of 161 MW. Significantly higher pressure ratios can be obtained by utilizing centrifugal compressors.

1.3 Application of Turbomachines

1.3.1 Power Generation, Steam Turbines

There is a wide range for application of turbomachines; a few of them are already mentioned above. The most important application field is electric power generation. Demand of electrical energy is covered by large (up to 1300 MW) and medium size (up to 400 MW) steam turbines, Fig. 1.1. Steam turbines of small size are used in the chemical and paper industry as well as in transportation systems. Hydraulic turbines are used primarily for electric power generation.

1.3.2 Power Generation, Gas Turbines

Another important application field of turbomachines is gas turbine technology. A gas turbine engine incorporates compressor and turbine components. As power generating units, gas turbines are used to cover the electric energy demand during peak load periods. The thermal energy of exhaust gases of a gas turbine can be used to generate steam for additional power generation. This is accomplished by a combined cycle which exhibits an efficient device for base load power generation with an overall thermal efficiency of over 55%. Figure 1.9 exhibits a conventional single-spool power

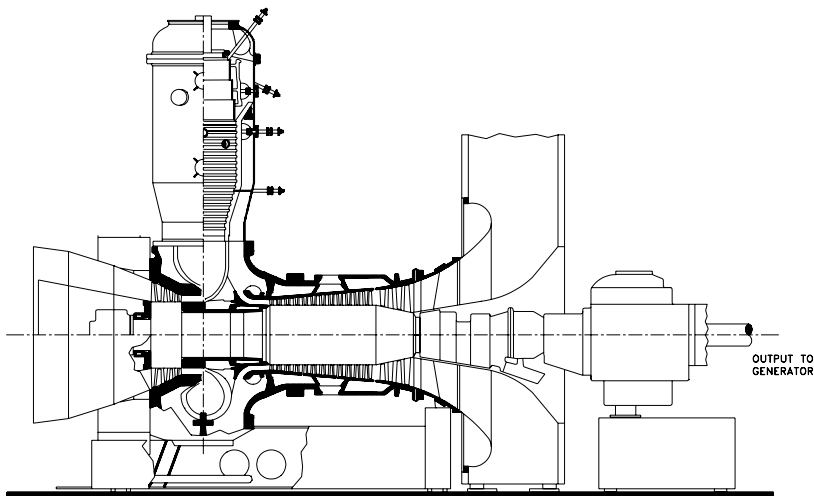


Fig. 1.10: Single-spool power generation gas turbine engine with a multi-stage compressor, a combustion chamber, and multi-stage turbine, (GT-9, ABB)

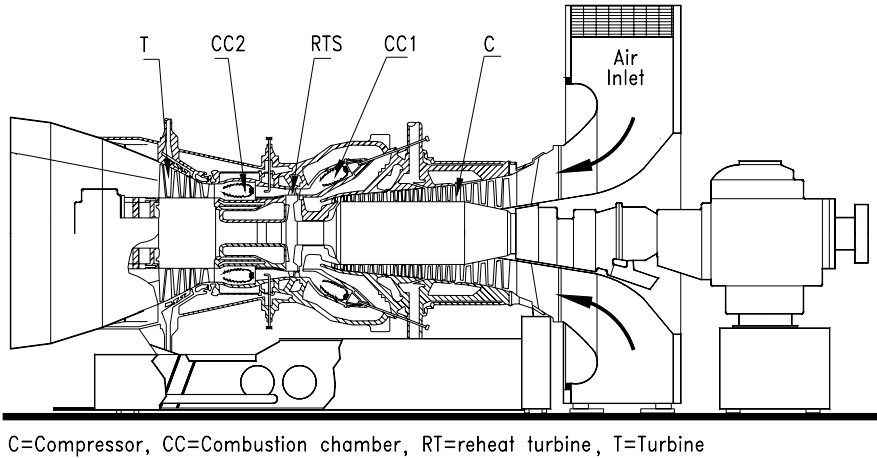


Fig. 1.11: Schematic cross- section of GT-24 gas turbine engine with a single stage reheat turbine and a second combustion chamber, ABB

generation gas turbine engine with a thermal efficiency close to 33%. To substantially improve the thermal efficiency without a significant increase in turbine inlet temperature, a well-known reheat principle as a classical method for thermal efficiency augmentation is applied. This standard efficiency improvement method is routinely applied in steam turbine power generation, and for the first time, in 1948, it was applied to a power generation gas turbine plant in Beznau, Switzerland, Fruttschi [1]. The plant is still operational after almost half a century, has a turbine inlet temperature of 600 °C, and an efficiency of 30%, which is remarkably high for this very low turbine inlet temperature.

Despite the predicted high efficiency at the conventional turbine inlet temperature, the sequential combustion did not find its way into the aircraft and power generation gas turbine design. The reason was the inherent problem of integrating two combustion chambers into a conventionally designed gas turbine engine. This issue raised a number of unforeseeable design integrity and operational reliability concerns. ABB (former Brown Boveri & Cie) was the first to develop a gas turbine engine with a single shaft, two combustion chambers, and a reheat turbine stage followed by a multi-stage turbine, Fig. 1.11.

1.3.3 Aircraft Gas Turbines

Besides power generation, gas turbines play an important role in transportation. Aircraft gas turbines are the main propulsion systems of large, medium, and small size aircrafts. As an example, a high bypass ratio aircraft gas turbine engine is shown in Fig. 1.12.

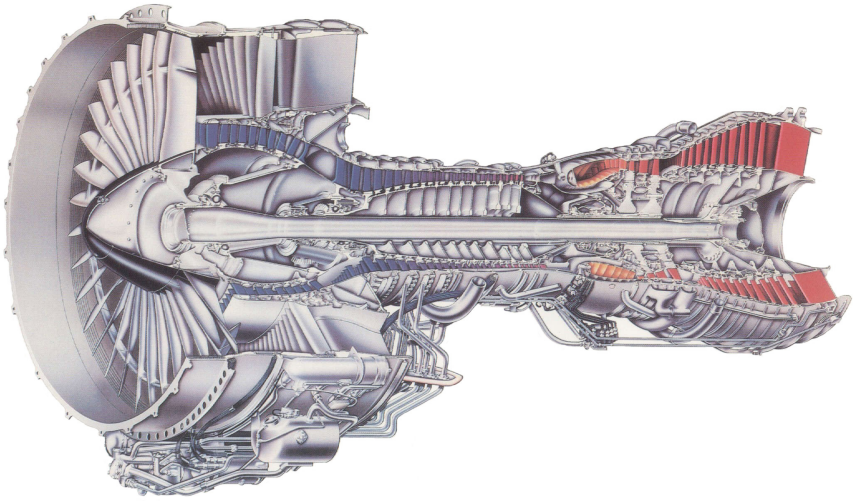


Fig. 1.12: Twin-spool, high bypass ratio aircraft engine (Pratt & Whitney)

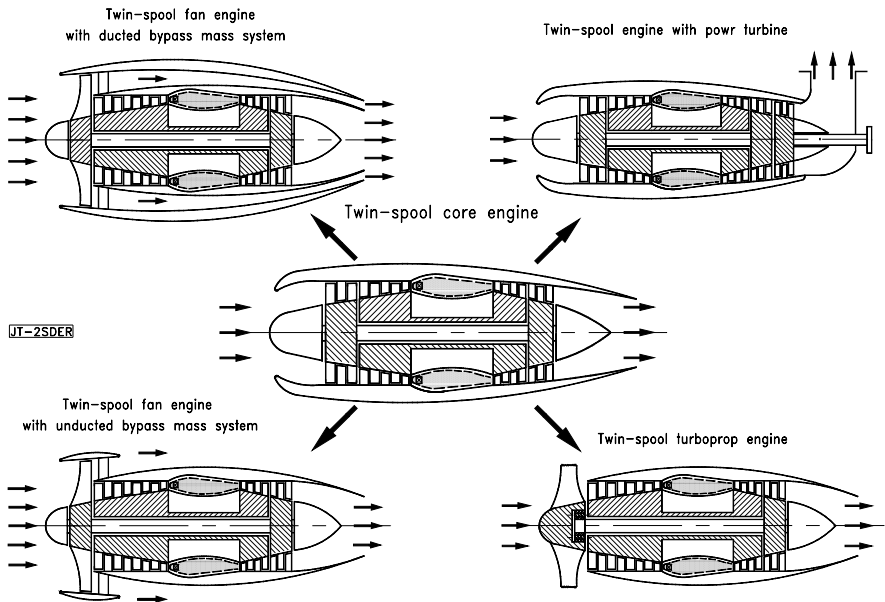


Fig. 1.13: Schematic of a twin-spool core engine with its derivatives

It consists of a *high pressure and a low pressure spool*. The low pressure spool carries the *fan stage* and the LP-turbine component. The HP- turbine drives the HP-compressor via the connecting shaft. The two spools running at two different rotational speed are connected aerodynamically with each other. Using a single spool or a twin spool core engine, a variety of derivatives can be designed to perform different functions as Fig. 1.13 suggests.

1.3.4 Diesel Engine Application

Turbochargers, which are small gas turbines, are applied to small and large Diesel engines, to increase the effective mean piston pressure and therefore improve the thermal efficiency of Diesel engine. As an example, typical turbocharger for large Diesel engines is shown in Fig. 1.14. It consists of an air filter, inlet nozzle, a radial compressor stage, driven by a single stage axial turbine. Exhaust gas from Diesel engine enters the turbocharger turbine side and drives the turbine. The turbine drives the compressor stage that sucks air from the environment and delivers it to the piston, thereby substantially increasing the mean effective piston pressure and thermal efficiency of the engine. High efficiency of 45% are achieved by turbocharging large large engines. The compression process is accomplished by a single radial impeller.

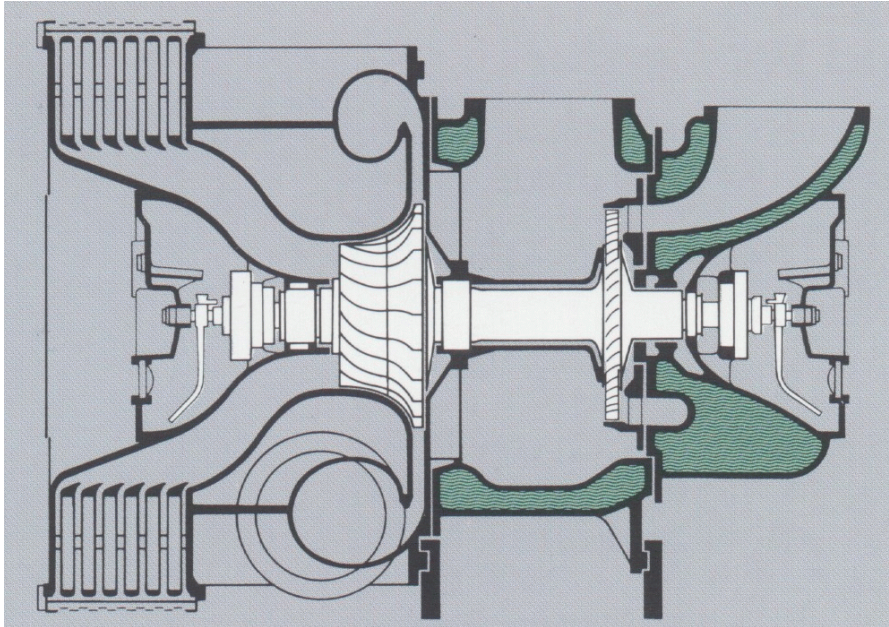


Fig. 1.14: Turbocharger for a large Diesel engine of 10 MW power, compressor pressure ratio 4.0:1 (ABB)

1.4 Classification of Turbomachines

Turbomachines are classified into different categories according to their specific applications. Following parameters determine the type of the turbomachines: (1) Working fluid, liquid or gaseous, (2) required power generation for turbines, (2) required pressure ratio and mass flow for compressors.

1.4.1 Compressor Types

Radial compressors are generally used for higher pressure ratios and small mass flow rates. For pressure ratios up to 35 and higher mass flow rates, axial compressors are used. For liquid working fluids, radial compressors (pumps) are common.

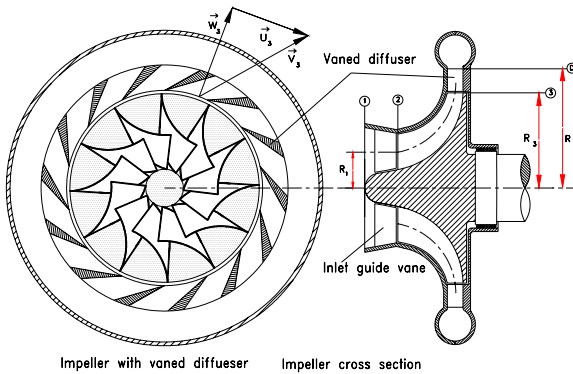


Fig. 1.15: Single stage radial compressor with an inlet guide vane and exit diffuser

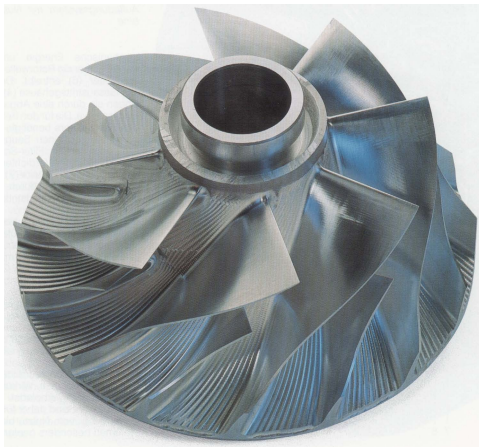


Fig. 1.16: Radial compressor rotor, 3-D image, front view, cross section

Figure 1.15 exhibits the cross section of a typical radial compressor rotor with the exit diffusers to reduce the exit kinetic energy of the working medium. A 3-D image of such a rotor is shown in Fig. 1.16.

1.4.2 Turbine Types

A significant criterion for selecting gas or steam turbine types is the mass flow. For small mass flow rates, both axial and radial turbines can be used. However, for higher mass flow rates the application of the axial type is the common practice. Hydraulic turbine types depends on the head and capacity of water sources. The axial type (Kaplan turbine) is especially applied to low head, high capacity; while the radial type (Francis turbine) is for medium head. For very high hydraulic head, a special water wheel (Pelton wheel) is used.

1.5 Working Principle of a Turbomachine

The conversion of total energy into shaft work or vice versa, can also be established with simple reciprocating (piston-cylinder) engines. Why should a turbomachine be applied? The answer to this question involves the limitation of power and mass flow associated with the reciprocating engines. The reciprocating engine, which works entirely on the displacement principle, is not able to transfer large amount of mass flow or mechanical energy. The largest operating Diesel engine has a power output of about 20 MW, whereas a large steam power plant may produce up to 1300 MW. Unlike the reciprocating engines the working principle of a turbomachine is based on exchange of momentum between the blading and the working fluid.

References

1. Frutschi, H.U.: Advanced Cycle System with new GT24 and GT26 Gas Turbines, Historical Background. ABB Review 1/94 (1994)